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Chapter 3

Active Flow Control by Using Plasma Actuators

Gabriele Neretti

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Abstract

Active flow control has recently received an increasing attention since it allows to directly manipulate the flow-field around a surface only when it is effectively requested. Aerodynamic plasma actuators supplied by a dielectric barrier discharge (DBD) can be used for this purpose. Usually, sinusoidal voltages in the range 5–50 kV peak and frequencies between 1 and 100 kHz are utilized to ignite this plasma typology. The surface discharge produced by these devices is able to tangentially accelerate the flow field by means of the electrohydrodynamic (EHD) interaction. DBDs generate non-thermal plasmas characterized by low input energies and limited temperature increments. Plasma actuators can be easily designed by following the shape of the aerodynamic body and can be used over heat-sensitive surfaces. These aerodynamic devices have demonstrated to produce boundary layer modifications with induced speeds up to 10 m/s. Their use over airfoils, flaps, and blades have shown the possibility to delay the transition between laminar to turbulent regime, to prevent flow separation enhancing lift and reducing drag. Moreover, the adoption of these actuators over landing gears and trailing edges may induce a noise reduction effect. Dielectric materials, electrodes configuration, and supplying waveforms are most relevant parameters to be considered to enhance actuator performance. On a parallel plane, on/off actuation strategy is a key point in the use of these devices when utilized over aerodynamic surfaces impinged within an external flow.

Keywords: Active flow control, Dielectric barrier discharge, Electrohydrodynamic interaction, Plasma physics, Noise mitigation

1. Introduction

The interest in flow control in the fluid dynamic domain has showed a quick growth in last 15 years [1] due to rapid development of sensors and actuators technologies. Even though passive control techniques are still attractive since they do not require an energy input, active control

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strategies have recently received more attention since they can be used in a selective way and can be operated only when it is effectively requested. Among different active techniques, plasma aerodynamic actuators are attractive because they present high dynamic responses due to the absence of moving parts, are characterized by low weight, are easy to build, are backward compatible with existing aerodynamic surfaces, and generate negligible aerodynamics interferences when they are switched off. When actuated, they can significantly modify the status of the boundary layer developing on the body surfaces. For this reason, they have been extensively studied for aeronautical applications to prevent flow separation enhancing lift and reducing drag [2, 3]. More recently, they have been used also to control friction drag by delaying transition [4, 5] or by oscillating the flow in spanwise direction [6], and to control global instabilities of the flow [2, 3, 7]. Due to these characteristics, the potential of plasma actuators has been extended to many other applications like for instance tip clearance flow control of turbines [8, 9], and wind turbine blades and holder [10, 11].

This brief review about DBD aerodynamic actuators is all but exhaustive. The main goals of this work are to give to the reader some basic knowledge about the physics of plasma actuators and to show most important applications of these devices into the active flow control domain.

2. DBD aerodynamic actuators: basic principles

Plasma aerodynamic actuators are based on the electrohydrodynamic (EHD) interaction generated by the so-called ionic wind. High electric fields can locally ionize the air. The produced heavy-charged species are accelerated by the applied electric field and, by means of collisions, they can yield momentum to the surrounding neutral gas. The force f per unit volume within the discharge can be yield by the following expression:

$$\mathbf{f} = \left(\mathbf{n}_\mathbf{i} - \mathbf{n}_\mathbf{e}\right)\bar{\mathbf{E}} \tag{1}$$

where E is the electric filed and n_i and n_e are ion and electron number density respectively.

First studies were conducted by using direct current (DC) corona discharges [2]. Main disadvantages of these actuators are low flexibility in electrodes configuration and in the supply system, and the transition into spark regime producing irreversible damage of the actuator itself.

Nowadays, the largest part of plasma aerodynamic actuators is based on the surface dielectric barrier discharge (SDBD). This typology of discharge allows to use several electrodes geometry, different supply voltage waveforms, and it prevents the transition into the arc regime due to the presence of the dielectric material. DBD actuators generate non-thermal plasmas [12], limiting power consumption and allowing their use over heat sensitive surfaces.

A classical DBD aerodynamic plasma actuator is constituted by a dissymmetric electrode pair separated by a dielectric slab (**Figure 1**). When high voltages (typically 10–50 kV at 1–100 kHz)

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are applied to the electrodes, a surface discharge is produced (**Figure 2**). Discharge appears to be macroscopically homogeneous to the unaided eye, but it is constituted by a sequence of micro-discharges [13] lasting typically for tens of nanoseconds with a repetition rate of several hundreds of megahertz. Fast ignition and quenching of the discharge can be inferred by voltage-current time behavior reported in **Figure 3**.

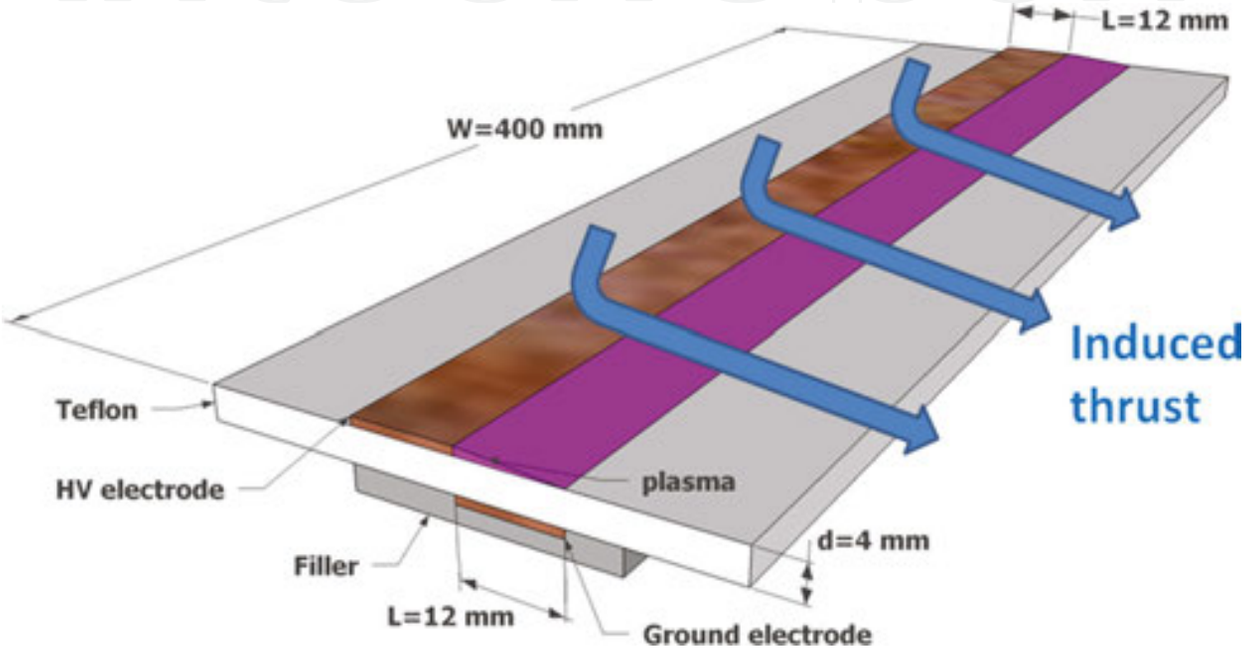


Figure 1. Schematic of a SDBD actuator for flow control.

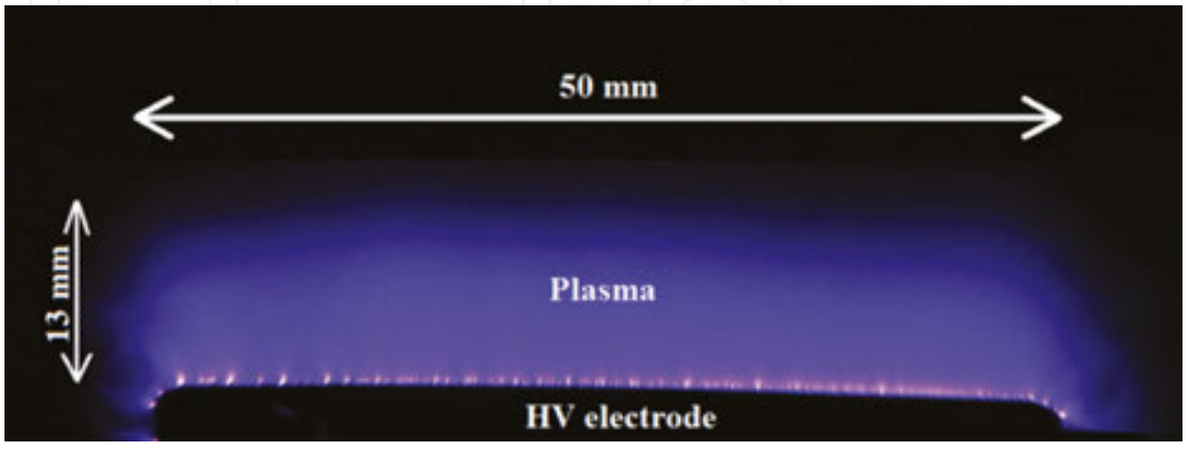


Figure 2. Top view image of SDBD discharge [14].

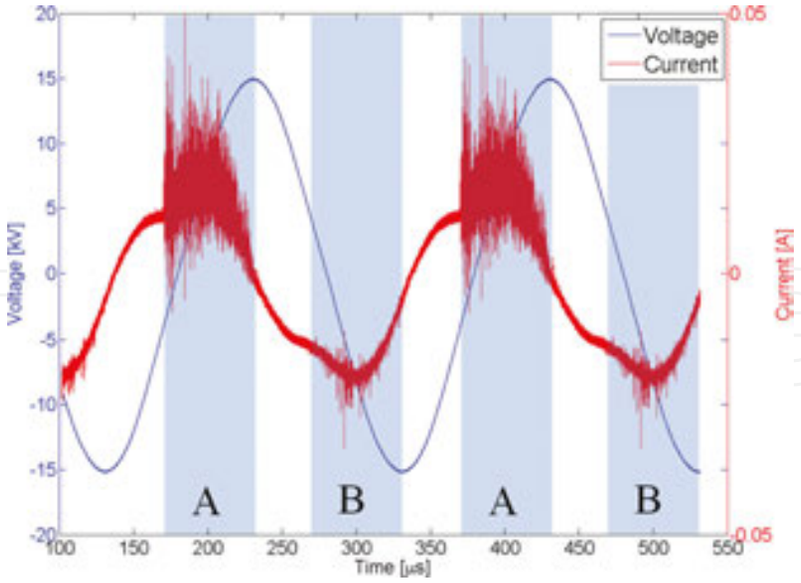


Figure 3. Voltage-current time behavior of a SDBD [15].

The presence of the plasma and the particular electrode configuration induce a jet tangential to the actuator wall, similar to a classic blowing technique [13]. These jets can modify the aerodynamic boundary layer, increasing flow momentum, at least in the near-wall region above the surface. A large number of experimental [14–25] and numerical [26–47] works have been done in last decade to understand basic physical phenomena involved in the EHD interaction.

A typical velocity profile induced by the tangential wall jet is shown in **Figure 4**. Measurements have been carried out by a glass Pitot tube positioned 2 mm downstream with respect plasma extension and moved parallel to the actuator surface. Maximum velocity of about 5–6 m/s are usually reached.

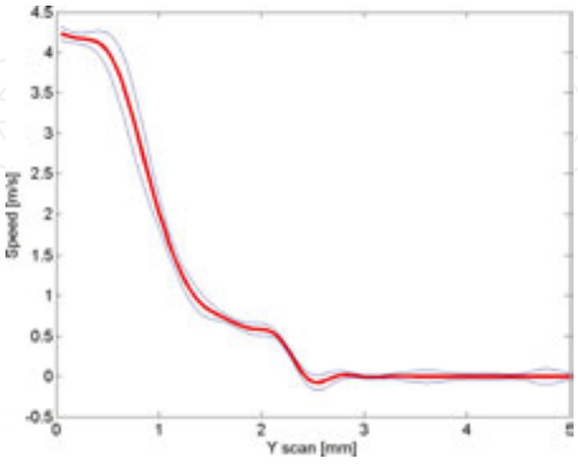


Figure 4. Typical pitot velocity profile of a DBD plasma actuator (red line). Blue lines represent standard deviation [48].

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Fast dynamics of these actuators is underlined in **Figure 5** where Schlieren images of the induced jet developing during ignition of the discharge are shown. Steady state (d) is typically reached after 400 ms after discharge ignition.

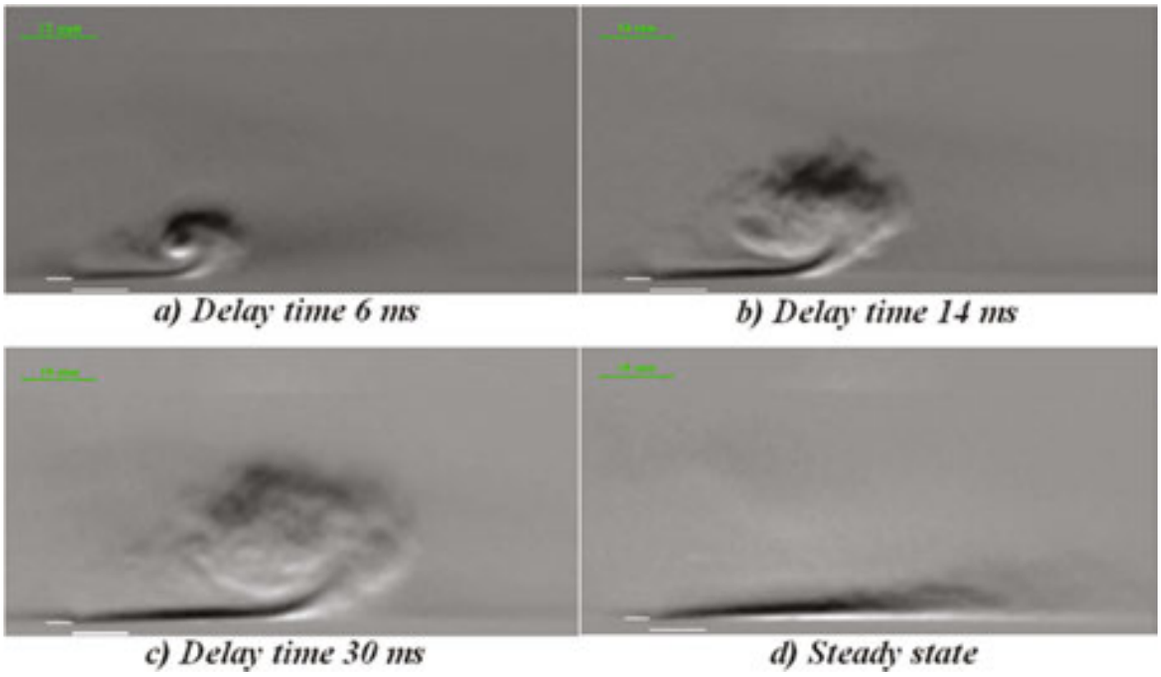


Figure 5. Schlieren images of induced wall jet during ignition phase of the discharge (a, b, and c) and steady state operation (d) [48].

As already introduced [26–47], EHD interaction produced by DBD plasma actuators has been numerically investigated a well. Main issues are related to the simulation of the discharge and its interaction with surrounding gas. A 'realistic' simulation of a DBD streamer should take into account gas ionization, plasma chemistry, thermal fluxes, diffusion of neutral and charged species, and charge deposition over dielectric surfaces. Time steps of about tens of picoseconds and mesh size in the order of few micrometers are usually required to reproduce the formation of a plasma filament lasting for tens of nanoseconds and featured with characteristic length of about few millimeters. Several coefficients related to diffusion, secondary electrons emission, reaction rates, and electrons attachment are often not easy to estimate or to recover from existing literature. The numerical model leads to the temporal/spatial evolution of the body force produced by the discharge. The second step is the coupling between the discharge and the surrounding gas. This is another numerical challenge because characteristic times and lengths of the discharge are several orders of magnitude smaller with respect those related to the fluid-dynamic domain. Several authors [26–36] followed this computational strategy obtaining interesting results in good agreement with experimental fluid-dynamic effects. In **Figure 6a**, integrated horizontal body force as a function of the applied voltage is shown [36]. The two half periods produce different force dynamics and magnitude. In **Figure 6b**, the time-averaged horizontal force distribution above the actuator surface is depicted [33]. Highest values have been obtained close to plasma end.

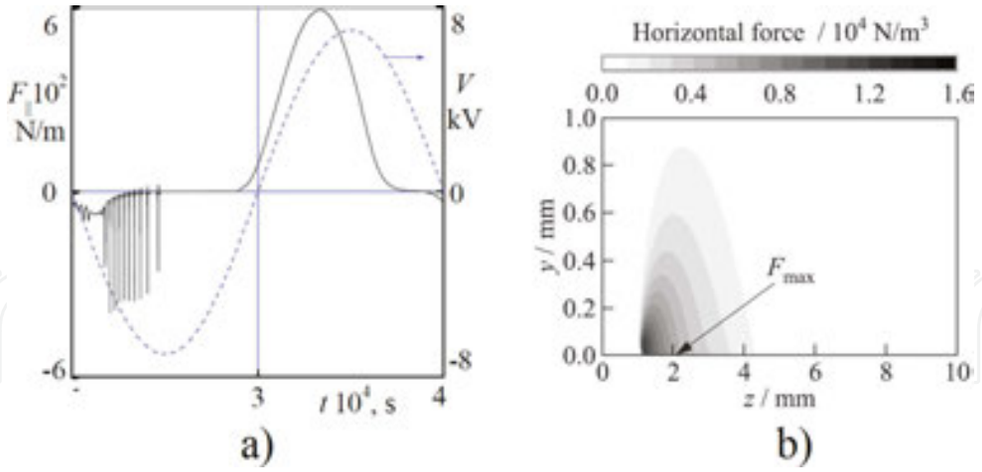


Figure 6. Time evolution of the EHD body force (a) [36], and spatial distribution of the average horizontal force (b) [33].

A simpler approach is to estimate the electron number density [37–42], on the basis of experimental measurements or theoretical calculations, and to evaluate EHD body force using Equation 1. This force is subsequently utilized as input parameter in the Navier-Stokes equation solver. A spatial/temporal average value of the body force can also be obtained by means of experimental results [43–47]. This method allows to use standard fluid-dynamic solvers avoiding difficulties arising from the couple between plasma and surrounding gas.

Both numerical and experimental works demonstrated the capability of plasma actuators to produce a thrust able to move surrounding gas in a desired direction. In order to increase both induced speed and region in which the actuator manifests its influence, a series of DBD actuators can be manufactured (**Figure 7**). Each actuator of this multi-electrode arrangement contributes to increase the induced speed.

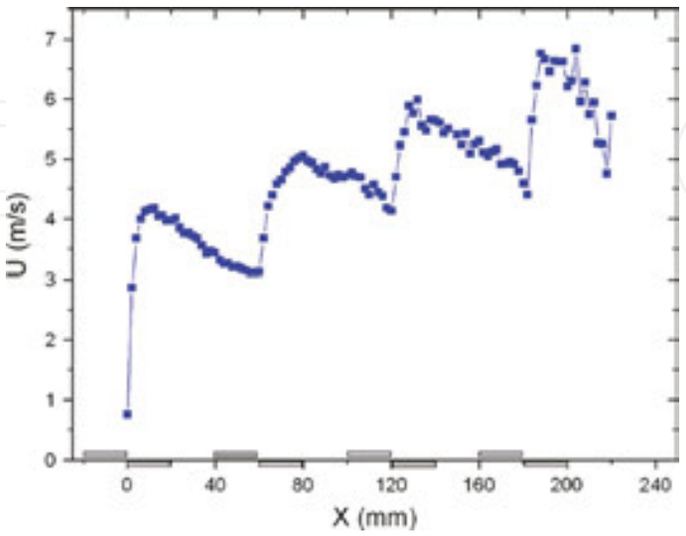


Figure 7. Horizontal velocity profile (y = 0.5 mm) above four DBD actuators in series [13].

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On a parallel plane, voltage waveform shape (arbitrary or nanopulsed signals) can enhance thrust of the induced jet, increasing effectiveness of actuators [15, 49–56]. The use of arbitrary waveforms can enhance plasma ignition phases in which induced thrust is higher. In this way, induced speed (**Figure 8**) and efficiency (**Figure 9**) can be both increased [15]. Nanopulsed discharges are able to generate energetic plasmas lasting for few nanoseconds. During the ignition of the discharge, a high amount of energy is deposited within the gas inducing local shock waves able to significantly modify the boundary layer of an incoming flow [56].

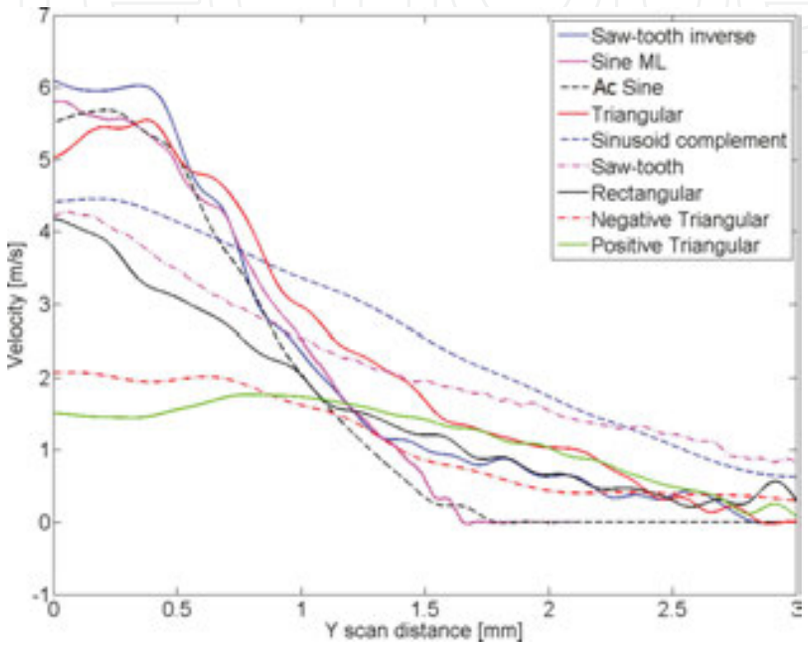


Figure 8. Pitot velocity profiles obtained close to plasma extension for different supplying voltage waveforms [15].

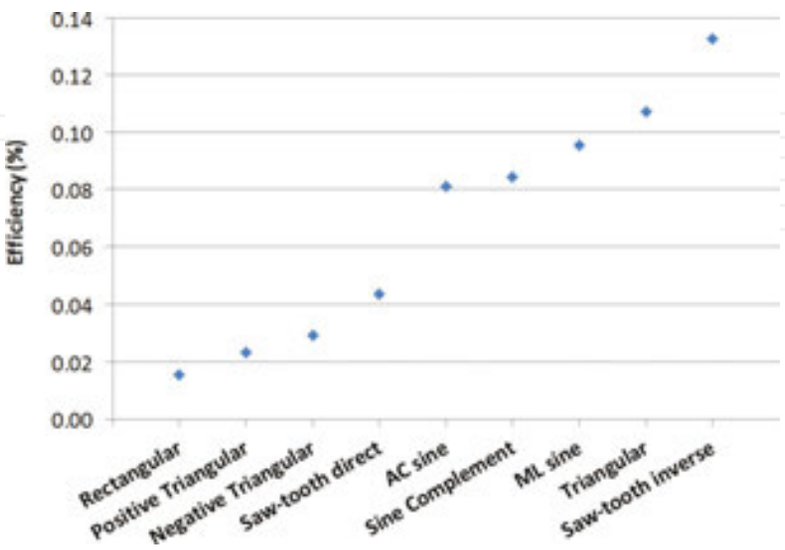


Figure 9. Electric into kinetic conversion efficiency for a DBD actuator driven with different voltage waveforms [15].

Another possibility to increase actuator performance is the adoption of a third exposed electrode supplied with high-voltage DC fields. In this way, a sliding DBD is generated. Depending on the sign of the DC field, it is possible to modify the morphology of the induced ionic wind [57, 58].

DBD actuators can be arranged to produce normal or vectorized jets, too. These devices can be used to mimic classical synthetic jets and are usually called plasma synthetic jet actuators (PSJA). Typical geometries are annular and linear one [48, 59–62]. In both cases, tangential wall jets collide merging in a unique-induced jet able to generate perturbations far away from the actuator surface (**Figures 10** and **11**). When the linear configuration is adopted, by supplying exposed electrodes with different voltages, it is possible to produce an induced jet with an arbitrary inclination. Three-dimensional flows can be also produced by using a classical DBD actuator, but with an exposed electrode characterized with serpentine or serrated geometries, instead of the usual linear one [63, 64]. This particular electrode geometry generates small tangential jets that collide and propagate downstream pushed by the EHD interaction body force.

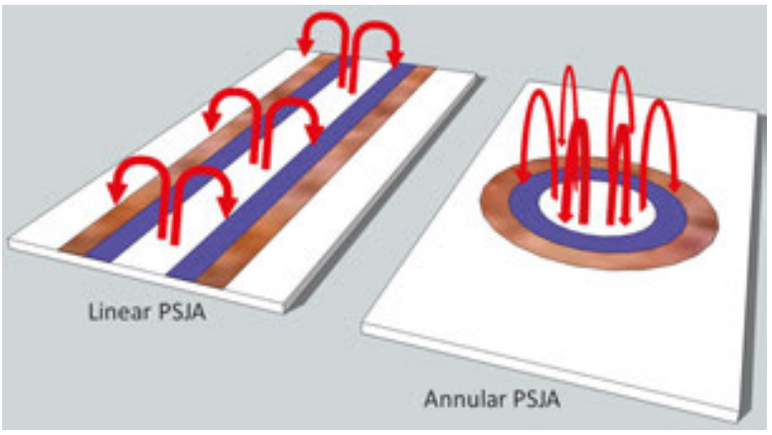


Figure 10. Induced normal jet of linear (left-hand side) and annular (right-hand side) PSJA.

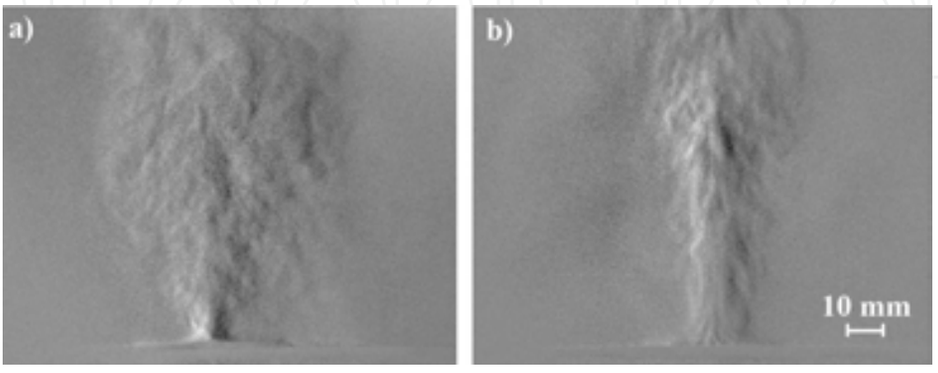


Figure 11. Schlieren images of PSJAs of linear (a) and annular (b) geometries. Electrode distance (a) and diameter (b) is 30 mm.

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3. DBD aerodynamic actuators: flow manipulation

In the last decade, DBD aerodynamic actuators have been extensively studied in the active flow control domain. Position and actuation strategies of these devices are key points in their effectiveness in flow control over aerodynamic surfaces. Many studies have been accomplished over airfoils [65–72], diffusers [73, 74], and wind [10, 11 and 75] and turbine [8, 9] blades, in order to enhance fluid-dynamic performance. Moreover, the adoption of these devices over landing gears and trailing edge surfaces have demonstrated the possibility to obtain a noise reduction effect [76–78].

DBD actuators can be usually positioned over aerodynamic surfaces in spanwise and streamwise directions. In the former, the induced body force is in the same direction as the incoming flow. In the latter, induced thrust is perpendicular to the free stream direction. In this case, the composition of these two flows produces vorticities propagating in the downstream direction.

In **Figure 12**, a NACA 0015 airfoil equipped with four spanwise DBD plasma actuators is shown. The four plasma regions are clearly visible in the figure as bluish strips. In this configuration, actuators produce a tangential wall jet directed downstream. The effect of this plasma device in the recovery of stall condition is depicted in **Figure 13**, where smoke visualization is reported. Experiments show how the most effective actuator is the one positioned on the airfoil leading edge, just before the region where separation occurs [66, 67, 79, 80].

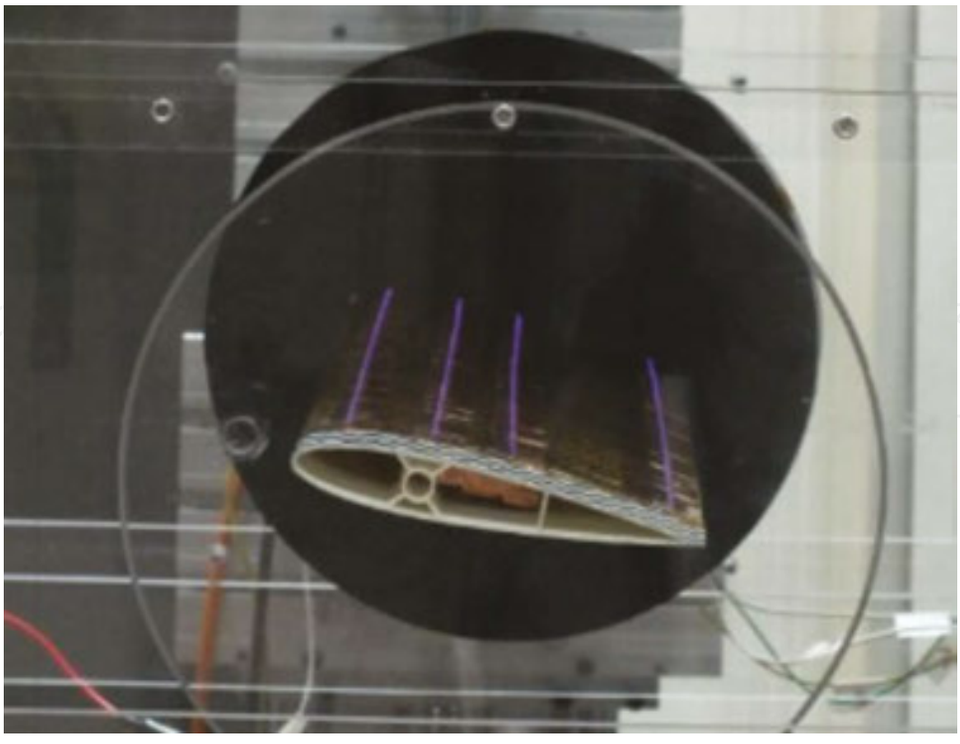


Figure 12. Airfoil equipped with four spanwise plasma actuators [65].

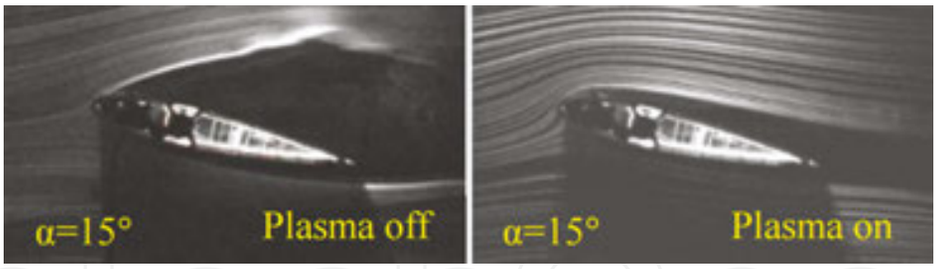


Figure 13. Flow structure around NACA0015 airfoil at Re = 15000 without (left-hand side) and with (right-hand side) plasma actuation [65].

When DBD actuators are streamwise mounted, induced and incoming flows combine together producing vorticities propagating in the downstream direction (**Figure 14**). Such a device can be used as a plasma vortex generator (PVG)

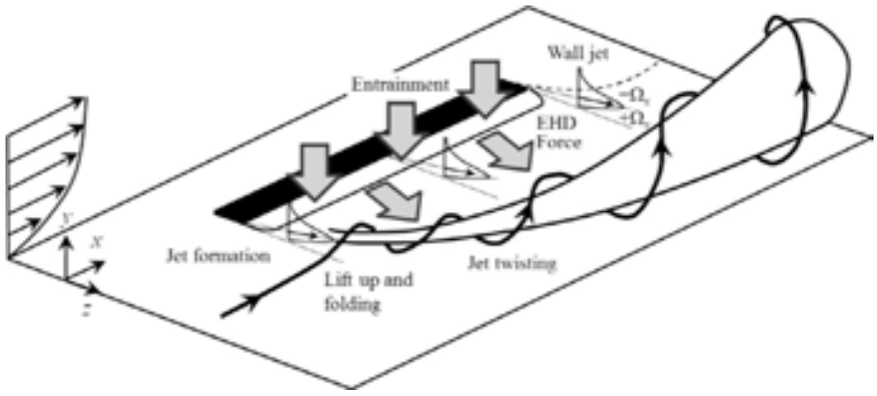


Figure 14. Vortex formation mechanism induced by a streamwise plasma actuator [8].

Changes in drag coefficient (C_D) and lift coefficient (C_L) by using a PVG are reported in **Figure 15**. At low Reynolds numbers, actuator effectiveness is very pronounced, leading to noticeable C_D reduction with a parallel increment in the stall angle.

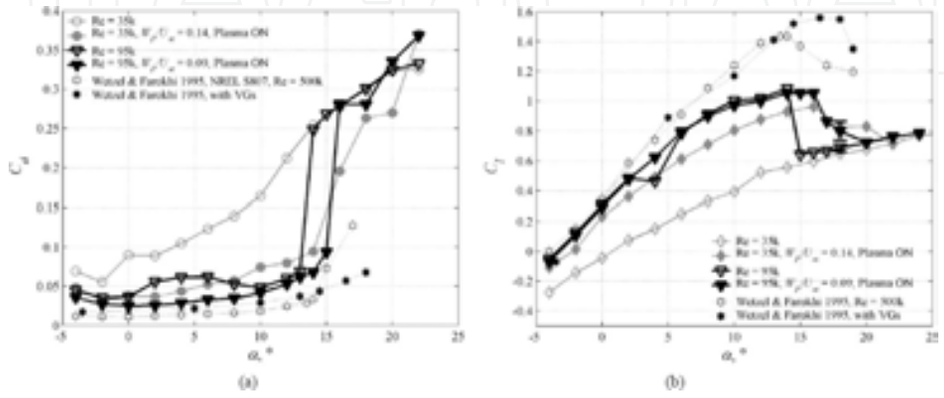


Figure 15. Drag (a) and lift coefficient enhancement (b) with counter-rotating PVGs on a NACA 4418 airfoil [8].

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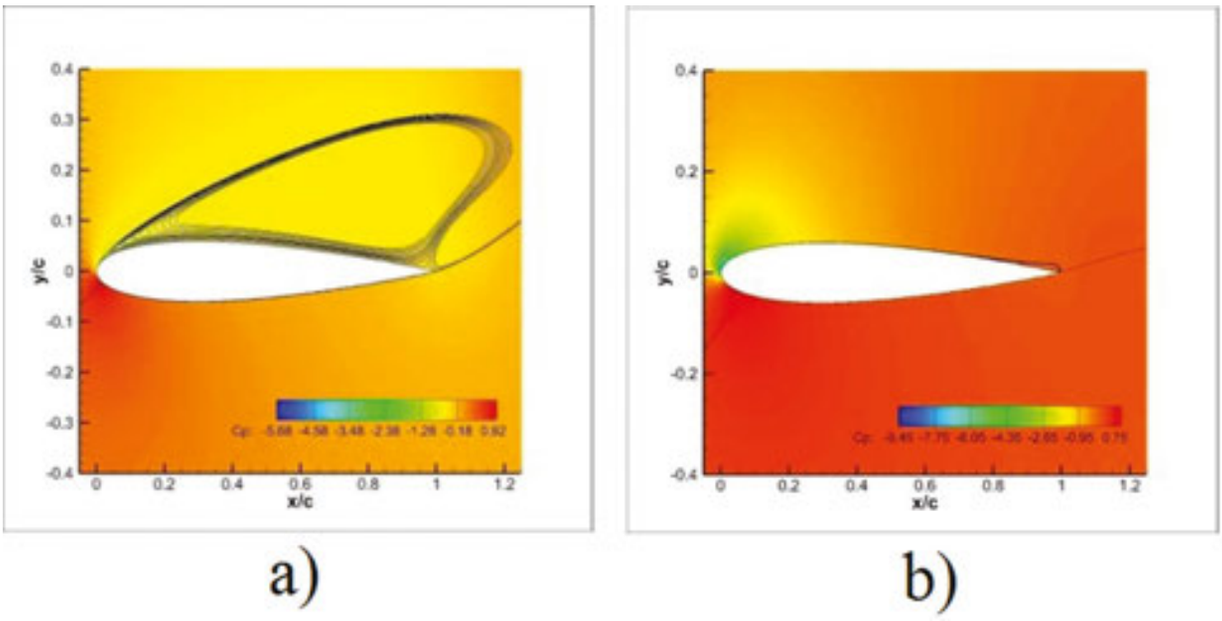


Figure 16. Pressure coefficient contours with streamlines over an airfoil with 15° angle of attack: plasma actuator off (a) and on (b) [47].

Effectiveness in flow control by means plasma actuators has been demonstrated by numerical works, too [47, 81–87]. In **Figure 16**, pressure coefficient contours with streamlines obtained over an airfoil with a 15° angle of attack are displayed. In **Figure 16a**, plasma actuator is switched off, and separation occurs. When the plasma device is activated, reattachment of the flow is achieved (**Figure 16b**).

Plasma actuators have demonstrated to strongly improve their ability in flow manipulation when operated with a duty cycle strategy [47, 66, 71, 72, 88]. With this approach, the DBD device is turned on and off with intermittence by following a particular duty cycle frequency. This frequency is usually chosen in the range 5–100 Hz and it is strictly related to natural vorticities developing over the aerodynamic surface. The percentage ratio between the period in which discharge is fed and the whole duty cycle period is called duty cycle percentage. If it

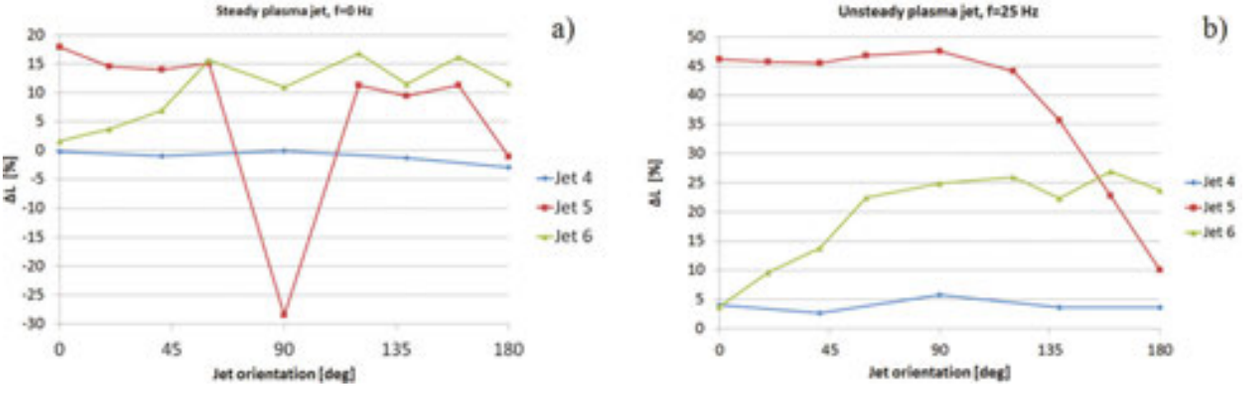


Figure 17. Lift recovery in percentage for different actuators location with a free stream velocity of 11 m/s: steady operation (a) and duty cycle operation (b) [66].

is fixed to 50%, it means that discharge is ignited half of the time. On a parallel plane, this actuation strategy leads to lower power consumption.

Figure 17 shows lift recovery in percentage of a stalled NACA0015 airfoil equipped with spanwise vectorized actuators located in different airfoil positions [66]. Jet 5 is generated by a DBD actuator located in the leading edge. When actuators are continuously operated, lift increments are limited to about 15%. When operated with a duty cycle strategy, lift increments are close to 50%.

Plasma actuators can also be used to reduce noise induced by aerodynamic surfaces, especially by landing gears and trailing edges [76–78]. Studies on bluff bodies have demonstrated the ability of DBD actuators to reduce downstream turbulence, leading to the suppression of particular tones or to an overall noise mitigation up to 4 dB.

4. Conclusion

Studies carried out in the last decades have demonstrated the possibility to use DBD aerodynamic actuators for active flow control purposes. In this last section, main advantages and disadvantages in the use of these plasma devices will be summarized.

Pros

- Possibility to locate these actuators in different positions on a surface and over existing aerodynamic bodies.
- Negligible aerodynamic interferences when they are not active.
- Fast actuation times.
- Low power consumption.
- Possibility to tune the on/off actuation strategy depending on the particular fluid dynamic condition.

Cons

- Induced velocity below 10 m/s.
- Low electric into kinetic conversion efficiency.
- Use of potentially hazardous high voltages and electromagnetic noise generation.
- Effectiveness in flow control for Reynolds numbers typically below few hundred thousand.

Disadvantages already introduced will be overcome only when a more detailed knowledge of basic interactions between discharge a neutral gas will be achieved. When higher induced speeds will be available, new and more effective flow control strategies will be developed.

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